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Report Title

Experiments on a quantum gate based on charge-phase superconducting

ABSTRACT

During this grant, we have invented, designed and successfully operated a new type of readout for charge-phase superconducting qubits. This new readout is based on the bifurcation of an RF-driven Josephson junction inserted in the loop of a split Cooper pair box. When the amplitude of the RF drive is in the vicinity of the bifurcation point, a small change in the effective critical current of the junction is amplified into a large phase change in the reflected signal. The performance reached by the device is in agreement with theoretical predictions. The speed of this readout is unprecedented: we measure in 20ns the critical current increment corresponding to the transition between the 2 states of the qubit. The repetition rate is 10Mz. We have performed a series of experiments showing that the amplification mechanism behaves as expected. No quasiparticles are produced during the readout and the back-action on the qubit when the readout is OFF is minimal. We have performed decoherence measurements at dilution refrigerator temperatures on the quantronium qubit integrated with RF readout. These measurements involve all possible 1-qubit gate operations. Compared with the DC readout method we have gained in repetition rate (factor of 100), signal-to-noise ratio on all coherence signals (factor of 10) but most importantly, on readout fidelity which now attains more than 60% (compared to 15%). This last improvement is very important for showing the entanglement produced by two-bit gate operations. The T1 has also been improved by 250%. We still have comparable T2 as before but we suspect this is due to insufficient filtering on the listening lines of our measurement apparatus and this problem is technically solvable.

In parallel with this work on readout and decoherence of the quantronium qubit, we have designed a new 2-bit gate based on capacitive coupling between qubits and worked out the complete protocol of pulses. Extensive numerical simulation this 2-bit gate protocol have been performed to assess the errors, which were found to be less than 1%. We have also successfully fabricated samples with correct parameters for this protocol.

During this period, our work has led to 3 published Physical Review Letters, we have submitted a review article for Physical Review, published 2 articles in the Journal of Quantum Computation and written an article for a conference proceeding.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

see attachment

Number of Papers published in peer-reviewed journals: 6.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

see attachment

Number of Papers published in non peer-reviewed journals: 2.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)

see attachment

Number of Papers not Published: 1.00

(d) Manuscripts

see attachment

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

R. Vijay (100%)

Number of Graduate Students supported: 1.00

Total number of FTE graduate students: 0.00

Names of Post Doctorates

Irfan Siddiqi (100%)

Number of Post Docs supported: 1.00

Total number of FTE Post Doctorates: 0.00

List of faculty supported by the grant that are National Academy Members

Names of Faculty Supported

Michel H. Devoret

Number of Faculty: 1.00

Names of Under Graduate students supported

Simon Fissette (10%)

Number of under graduate students: 1.00

Names of Personnel receiving masters degrees

Number of Masters Awarded: 0.00

Names of personnel receiving PHDs

Number of PHDs awarded: 0.00

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Inventions (DD882)

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Experiments on a quantum gate based on charge-phase superconducting qubits

**Principal Investigator: M. H. Devoret
Applied Physics, Yale University**

FINAL REPORT

Period April 1, 2002 – August 31, 2005

Summary: During this grant, we have invented, designed and successfully operated a new type of readout for charge-phase superconducting qubits. This new readout is based on the bifurcation of an RF-driven Josephson junction inserted in the loop of a split Cooper pair box. When the amplitude of the RF drive is in the vicinity of the bifurcation point, a small change in the effective critical current of the junction is amplified into a large phase change in the reflected signal. The performance reached by the device is in agreement with theoretical predictions. The speed of this readout is unprecedented: we measure in 20ns the critical current increment corresponding to the transition between the 2 states of the qubit. The repetition rate is 10Mz. We have performed a series of experiments showing that the amplification mechanism behaves as expected. No quasiparticles are produced during the readout and the back-action on the qubit when the readout is OFF is minimal. We have performed decoherence measurements at dilution refrigerator temperatures on the quntronium qubit integrated with RF readout. These measurements involve all possible 1-qubit gate operations. Compared with the DC readout method we have gained in repetition rate (factor of 100), signal-to-noise ratio on all coherence signals (factor of 10) but most importantly, on readout fidelity which now attains more than 60% (compared to 15%). This last improvement is very important for showing the entanglement produced by two-bit gate operations. The T1 has also been improved by 250%. We still have comparable T2 as before but we suspect this is due to insufficient filtering on the listening lines of our measurement apparatus and this problem is technically solvable.

In parallel with this work on readout and decoherence of the quntronium qubit, we have designed a new 2-bit gate based on capacitive coupling between qubits and worked out the complete protocol of pulses. Extensive numerical simulation this 2-bit gate protocol have been performed to assess the errors, which were found to be less than 1%. We have also successfully fabricated samples with correct parameters for this protocol.

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I. Goals

Our proposal for building a quantum information processor is based on a new type of superconducting qubit [D. Vion et al. Science 296, (2002) 886], the charge-phase qubit, also known as the "quantronium". The advantage of this qubit is its simplicity, its potential scalability and its very good coherence performance. The present grant started within a few days of the acceptance by Science of the manuscript- written the P.I. and his collaborators while he was still at CEA-Saclay - describing the design and operation of this novel superconducting qubit. This system consists of a single Cooper-pair transistor in parallel with a large Josephson junction (see Fig. 1). The superconducting loop thus formed is biased at null flux while the island of the transistor is charge-biased at the half-Cooper-pair point. At this "sweet spot" working point, the two lowest levels of the qubit have a transition frequency which is insensitive to first order to charge and flux noise, in contrast with all other superconducting systems proposed so far. The inconspicuous character of the qubit is reinforced by a particularly favorable choice of the ratio of the Josephson energy to the charging energy, which minimizes the influence of the environment while keeping the non-linearity of the system at an acceptable level. Quantum information is written into the qubit using the gate of the transistor while the quantum state of the qubit is readout using the phase degree of freedom of the large junction, hence the other name charge-phase for this new tunnel junction circuit.

The experiments performed by the P.I. and his collaborators at Saclay demonstrated that the coherence quality factor for this new qubit can attain 50000. This result was obtained by borrowing a technique from the domain of atomic clocks, namely a Ramsey fringe experiment. The decoherence time of the charge-phase qubit is thus over 100 times longer than what had been previously achieved by Nakamura et al. [Nature **398**, 786 (1999)] and allows for about 1000 one-qubit operations. The ultimate goal of the present grant is to explore how quantum-gates based on this new type of superconducting qubit would perform. A first important sub-task of this proposal is to improve the readout for this qubit. In the results of the Saclay experiment, the low readout efficiency was puzzling (since then, experiments by other investigators have also shown lower-than-expected readout fidelities). We had about 15-20% fidelity (defined as the probability of detecting a 1 when the qubit is in state 1 minus the probability to detect 1 when the qubit is in state 0). The phase readout we were using allows in principle 95% fidelity. A high readout fidelity is of crucial importance in experiments on quantum gate operation for the following reasons:

- a) During the initial tuning stage of the qubits (parameter-finding sequence), information on the parameters of the qubit should be acquired at the maximum possible rate to leave the maximum time window for the operation of the gate itself and to allow feedback for maintaining the qubit at its optimal tuning point.
- b) With high readout efficiency one can explore the mechanisms limiting decoherence with better signal/noise ratio and therefore distinguish between competing mechanisms.
- c) The precision on the correlation table qualifying the fidelity of the gate is of order 2 in the precision of the readout. A readout discrimination power of 20% does not limit the observation of Rabi oscillations and Ramsey fringes very much. However, it taxes very severely the observation of the violation of Bell's inequality proving that the quantum gate functions as it should.

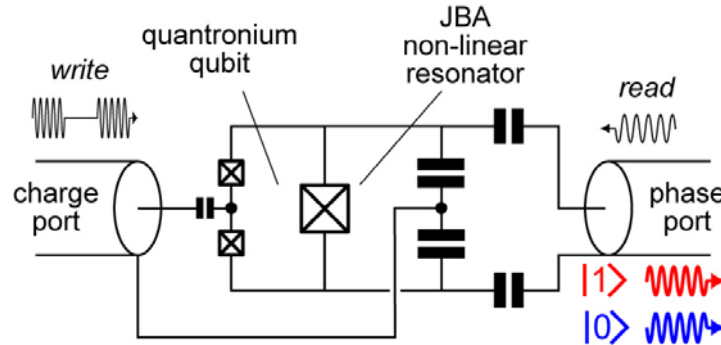


Fig. 1: Principle of the quantronium qubit with RF readout (Josephson Bifurcation Amplifier or JBA). The Josephson tunnel junctions are represented here by cross-in-box symbols. The qubit degree of freedom is the number of Cooper pairs in the island between the two small junctions (black dot). The two small junctions form a loop in which a large junction, used for read-out, is inserted. Two capacitors in series shunt the readout junction to lower its plasma frequency around 2GHz, away from the qubit transition frequency which is in the range 15-20GHz. Write signals prepare the qubit in one particular state. A readout signal, red-shift detuned from the plasma frequency, excites the non-linear resonant tank circuit consisting of the readout junction and its shunt capacitor. The phase ϕ of reflected signal is measured with a cryogenic HEMT amplifier. No change in the amplitude is observed on the reflected signal since no power is dissipated in the superconducting circuit chip. Adjusting the readout amplitude slightly below the bifurcation point of the non-linear tank circuit, ϕ takes two values separated by an angle close to 180 degrees depending on whether the qubit is in state 0 to 1. This phase change is resolved in about 100ns while the measurement of the state takes itself less than 20ns. The readout measurement can be performed with a repetition rate of more than 4MHz.

We believe that the quasiparticles which are generated when the large junction switches to its voltage state can degrade coherence. These excitations can cause the critical current of the junction to fluctuate, affecting in turn both the quantum coherence of the system, and increase the effective noise temperature of the readout junction. The problem with the now old Saclay readout is that a DC pulse is applied to the large junction. Our work at Yale is focusing on the operation of a quantronium qubit integrated with the Josephson Bifurcation Amplifier (JBA) readout which employs an RF pulses instead of a DC pulse (see Fig. 1) . With such a pulse, the junction is never driven in the normal state and does not produce any quasiparticles, thereby keeping the $1/f$ noise to a strict minimum.

II. Scientific results obtained during this grant

1. Invention of a new type of readout using RF pulses only

Our scheme is based on the following principle: the large junction used for readout (see Fig. 1) can be considered as a non-linear oscillator of the type studied first by Dykman and Smelianskii [Sov. Phys. JETP 67 (1988) 1769]. It is driven below the resonant frequency, which here is the plasma frequency of the junction, and the drive amplitude is adjusted just below the bifurcation point. When a small increase in drive amplitude drives the system across the bifurcation point, or

equivalently, when the critical current of the junction is reduced slightly, the system switches from a low amplitude, phase-leading state, to a high amplitude, phase-lagging state. The switching is hysteretic and this phenomenon allows latching in exactly the same way as the usual DC switching of the junction to the voltage state does.

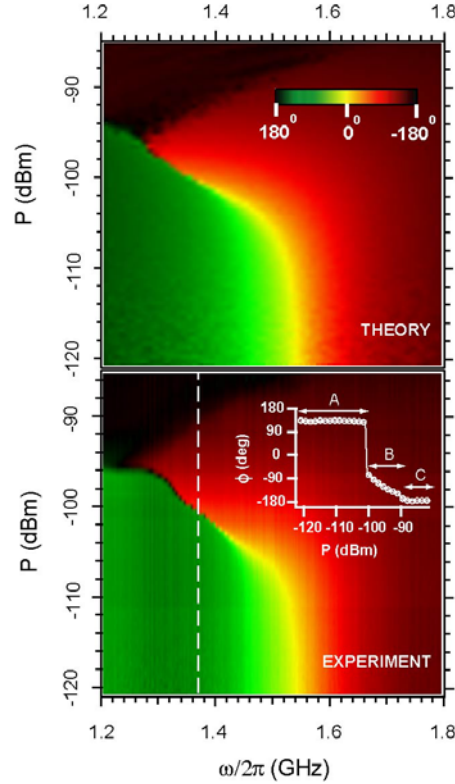


Fig. 2 Phase diagram, as a function of drive frequency and power, or the oscillation state of the readout junction, monitored by the phase ϕ of the reflected signal measured in the experiment shown on Fig. 1. The cut indicated by the white dashed line shows the bifurcation between two oscillation states. This bifurcation is exploited for amplification in the readout of the qubit.

This phenomenon is very sensitive and leads to an amplification process we have called bifurcation amplification. We have built the experimental apparatus for the measurement and first tested the bifurcation amplifier readout down to a temperature $T=250\text{mK}$ (see Figs. 2 and 3). The phase shift between the phase-leading and the phase-lagging state is detected in the following way. We mix the amplified signal with a reference signal near the plasma frequency. This reference signal is phase-locked with the primary signal sent to the drive pulse shaper. The shaper also uses a mixer for which the intermediate frequency signal port is fed by the pulse envelope sent. The effect of the mixing with the reference signal is to convert the phase shift of the voltage signal into a phase shift of the demodulated signal which is obtained after a filtering stage. The resulting signal has frequency components in the 80-100MHz frequency range and can be detected directly by a fast digital storage oscilloscope and accumulated if the experiment needs to be repeated.

The results of the measurement of the phase shift as a function of frequency and amplitude of the drive signal is shown on Fig. 2. Excellent agreement between theory and experiment is found. The phase diagram obtained in this way allows us to map exactly the location of the bifurcation

point. We show on Fig. 3 the results of a measurement of the hysteresis of the bifurcation phenomenon. An RF pulse with triangular envelope is applied to the junction, ramping the RF current up and down through the hysteresis region. In the center of the sweep, two values of the phase are measured, depending on whether the amplitude is ramped up or down.

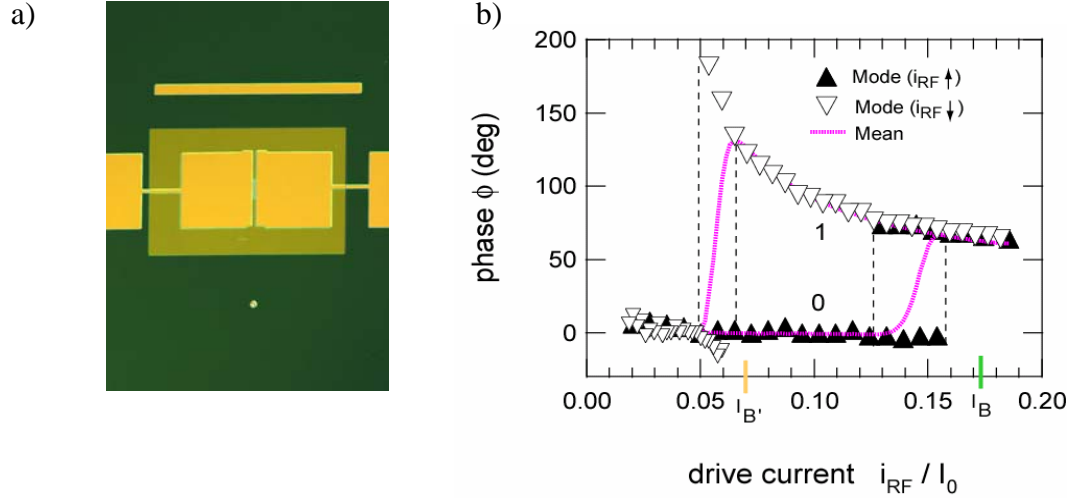


Fig. 3: a) On-chip Cu/Si₃N₄/Al microwave tank circuit for Josephson Bifurcation Amplifier (JBA). Yellow bar is 1 mm long. b) Operation of the JBA: A triangular RF pulse lasting 2 μ s drives a non-linear tank circuit based on a Josephson junction. The phase ϕ of the reflected signal is measured. The figure shows the hysteresis of the phase as the amplitude of the RF signal is swept past the two bifurcation currents I_B and $I_{B'}$. The abrupt latching transition between the two oscillation states 0 and 1 is exploited to readout the two qubit states. Hysteresis is clearly observed. Each symbol corresponds to a measurement of 10000 events. The up (down) pointing triangles correspond to the mode of the phase observed during the ramp up (down). The continuous line corresponds to the average phase. In between the dashed line a bimodal distribution of phase is observed. The parameter $\alpha=0.22$ at which this data is taken corresponds to the dimensionless detuning from the plasma frequency.

2. Microwave measurements at dilution refrigerator temperatures of samples integrating of readout with qantronium qubit

During the last part of the grant we have successfully performed dilution refrigerator measurements on the new JBA readout with the qantronium qubit. We have realized new improved samples with less parasitic metallic electrodes (see Fig. 4), and the whole chip is now placed in a sample holder mounted in good thermal contact with the mixing chamber of our new dilution refrigerator at Yale. The temperature of the sample is 10mK. We have performed experiments sending microwave pulse to the sample and listening to the reflected pulse on the readout line with a HEMT amplifier immersed in the bath at 4K.

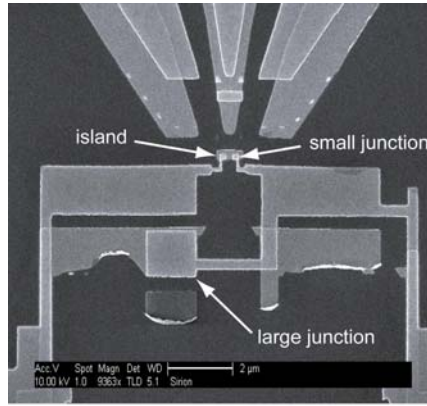


Fig. 4: Electron micrograph of Quantronium+JBA sample. The write port is the coplanar waveguide coming from the top. The read port are the two leads leaving the picture at the bottom. The sample is made by double-angle shadow mask evaporation, hence the doubling of certain features. The lift-off removes certain features that are parasitic but also produce electrodes that appear to be teared-off, like those in the vicinity of the large junction.

3. Write-readout protocol

We have also combined our pulse protocol for the readout junction with the pulse protocol for preparing the qubit. No discernable influence of the write pulse is seen on the readout junction that would modify its behavior. By adjusting the readout parameters (critical current of junction, detuning of the carrier of the readout pulse with respect to the plasma frequency) we have obtained a phase swing $\Delta\phi$ between 100 and 180 degrees, which is more than enough to decide whether the tank circuit has switched (measurement state 1) or not (measurement state 0) (see Fig. 5).

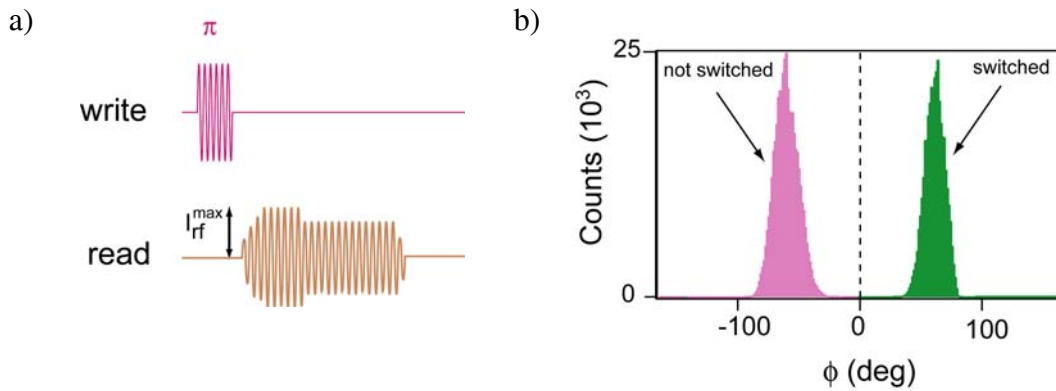


Figure 5: a) Protocol schematics representing as a function of time the combination of write and read signals sent to the charge and phase ports respectively. The example of write pulse shown here places the qubit in the 1 state (analog of an NMR π pulse). The readout pulse consists of a ramp-up section during 20ns, a measurement section during 20ns where the rf current amplitude is maximum, a latching section lasting 100ns, and a ramp-down section lasting 10ns. b) Histogram of average phase of reflected signal during the latched section of the readout pulse shown in a). The histogram consists of two separated peaks corresponding to the measurement of a switched or not switched tank circuit. The maximum amplitude of the pulse has been adjusted to give two equal peaks.

4. Measurement of fidelity of the JBA readout

The fidelity of the readout is the probability to detect a switching of the tank circuit (measurement state 1) 1 if the qubit is prepared *free* in the $|1\rangle$ -state minus the probability to detect no switching if the qubit is prepared *free* in state $|0\rangle$. The fidelity thus takes into account the errors coming from the loss of polarization of the qubit due directly or indirectly to the back-action influence of the readout circuit. For the JBA, we have presently demonstrated a fidelity between 48% and 62%. In Fig. 6 we show the fidelity measurement corresponding to our longest-lived qubit (see below).

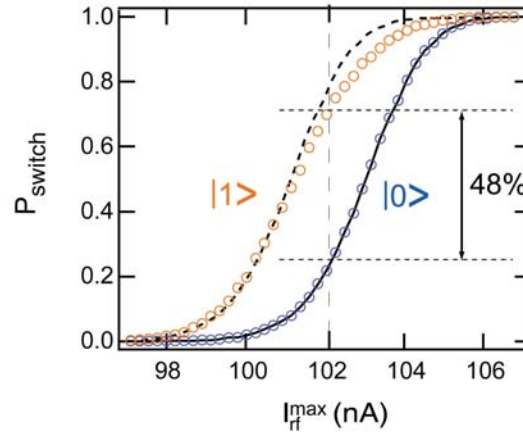


Fig. 6: Measurement of the probability that the reflected pulse phase switches from $\phi=0$ to $\phi=180$ during the readout sequence, when the qubit is left in its ground state (blue dots) or when it is placed in its first excited state after a π pulse (red dots). By optimizing the RF amplitude (dashed vertical line) we can obtain a readout fidelity of 48% in this particular sample. Some of the loss of fidelity can be attributed to the relaxation of the 1 state during readout, which manifests itself here as a rounded shoulder of the red dot curve when compared to the curve (dashed line) obtained by shifting the blue dot curve.

5. Preparing the qubit: 1-pulse and 2-pulse protocols

Several experiments probing decoherence have been performed on our qubits samples. After determining by spectroscopy the Larmor frequency of the qubit (data not shown) we first perform Rabi oscillations measurement by sending one pulse of varying duration on the gate port immediately followed by a readout pulse (see Fig. 7a). The frequency of the Rabi oscillation is then studied as a function of the pulse amplitude. Finally the energy decay time T_1 is measured by varying the wait time between the write pulse and the readout pulse. The measurement of dephasing requires a two-pulse experiment shown on Fig. 7b. The population of the excited state of the qubit is measured immediately after the second pulse, but the idle time during the two $\pi/2$ pulses is varied.

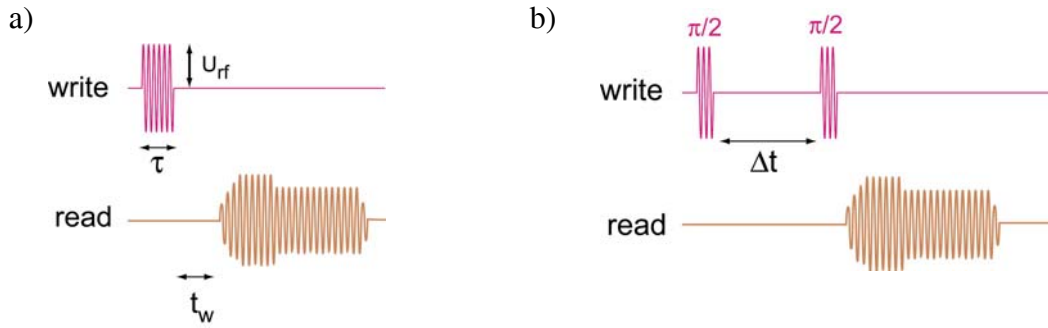


Fig. 7: Depending on whether we measure Rabi oscillations and T_1 on one hand or dephasing on the other hand, we are using a 1-pulse protocol (a) or a 2-pulse protocol (b).

5. Decoherence measurements results

We summarize the results of our decoherence measurements in table 1 below. Two samples were completely characterized. They differed in the area of the small junctions which affected the ratio of the Josephson frequency to the Coulomb energy, as well as the Larmor frequency.

Sample	$\omega_{01}/2\pi$	E_J/E_C	$T_1(\mu s)$	$T_2(\mu s)$	$T_{ech}(\mu s)$	F_{exp}	F_{thy}	F_{exp}/F_{thy}
A	18.989	6.0	1-1.5	300	300	0.61	0.7 ± 0.05	0.87
B	9.513	2.7	1.5-4	320	450	0.48	0.7 ± 0.05	0.69

Table 1: Results of decoherence measurements on 2 samples with different Larmor frequencies and E_J/E_C ratio. The fidelity is denoted by F .

In Fig. 8 we show the results of the Rabi oscillation measurement on sample B.

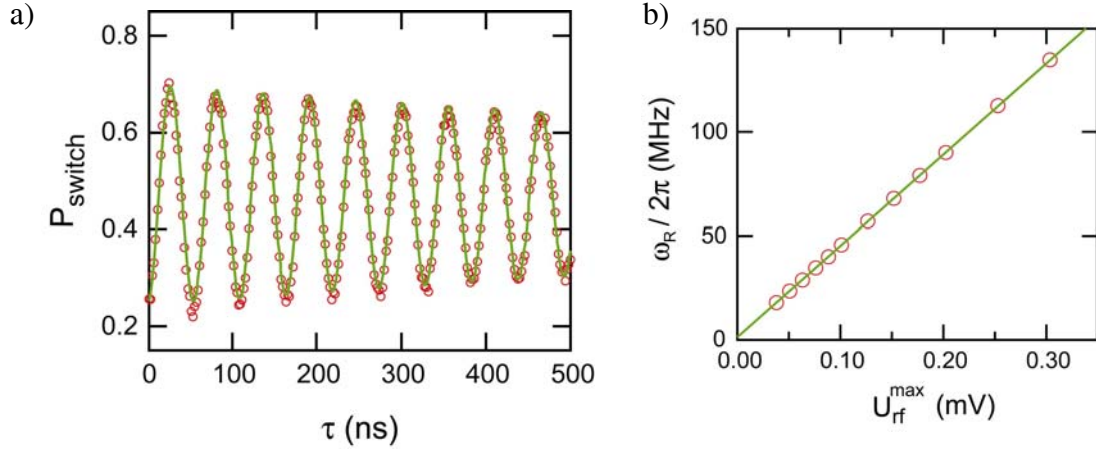


Fig. 8 a) Rabi oscillations as a function of the preparation pulse duration, for a pulse amplitude of 0.04mV. b) Rabi oscillation frequency as a function of the pulse amplitude.

An important result which was also obtained in these measurements was that we have been able to extend the Rabi frequency beyond 100MHz (see Fig. 8). This is important for performing fast one qubit operations.

In Fig. 9 we show the results of the T_1 and T_2 measurements. The relaxation time T_1 has improved compared with our original Saclay data but not T_2 . We believe that insufficient filtering in our microwave lines in the listening side and we are presently trying to correct this problem.

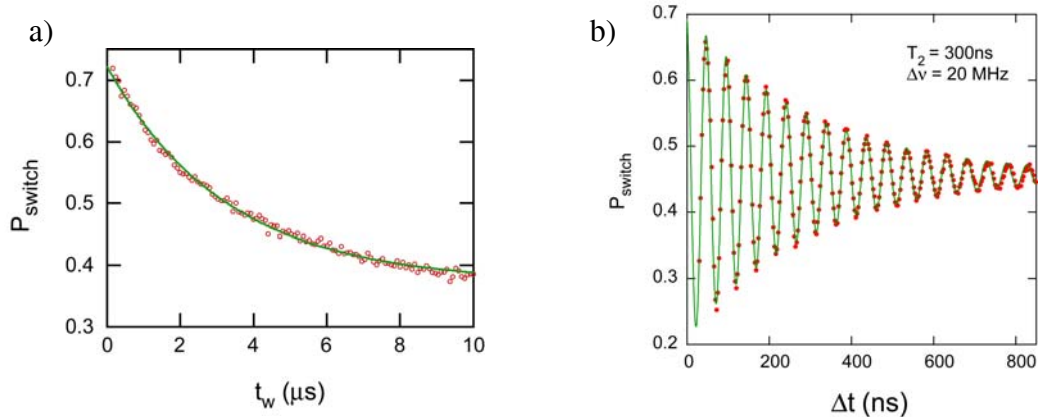


Fig. 9: a) Result of the measurement of the qubit relaxation time T_1 for the quantonium+JBA sample shown in Fig. 6. An improvement of T_1 by 250% is now observed compared to initial measurements of the quantonium. b) Measurement of Ramsey oscillations for sample A. The quality factor for dephasing is around 30,000, compared with the original 50,000.

4. Invention of a new gate protocol

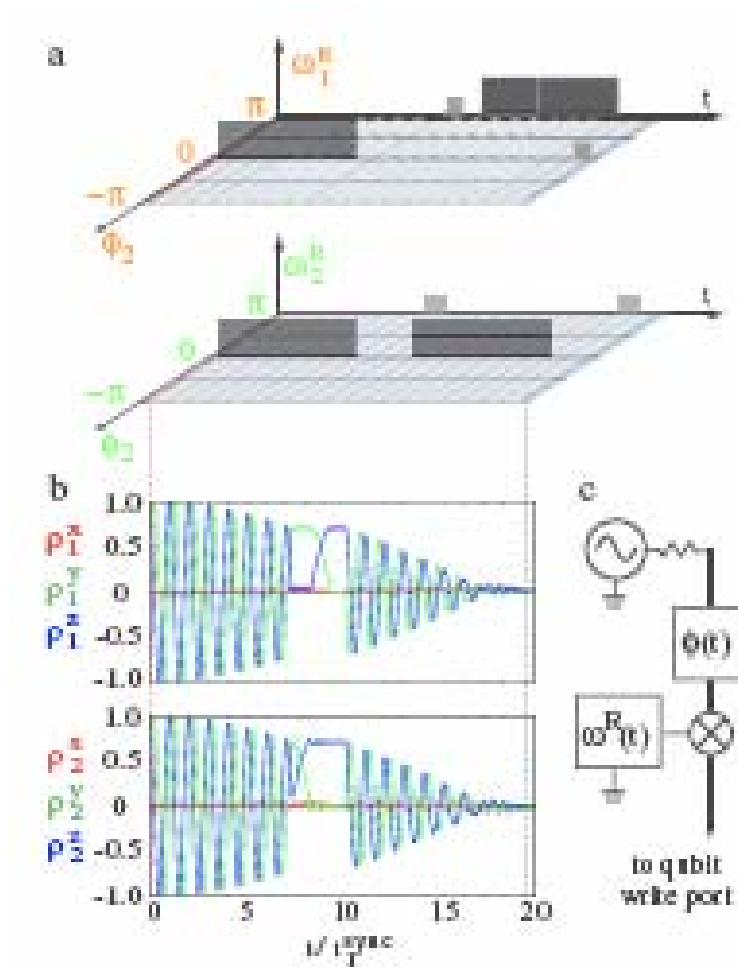


Fig 10: (a) Polar representation of pulse sequence for universal two-qubit gate (SWAP)^{1/2} using FLICFORQ. The sequence consist of two-qubit pulses (black) and one-qubit pulses (gray). (b) Sample simulation of pulse sequence using the full time-dependent Hamiltonian. Initial state is $|00\rangle$. . Simultaneous vanishing of each reduced density operator indicates generation of maximally entangled state. Final state is $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, gate fidelity is >99%, with errors due to Bloch-Seigert shift. Plotted are the components of each reduced density operator. (c) Schematic experimental set-up for producing pulses to implement universal gates with FLICFORQ.

During this grant we have also invented a new protocol for a gate operation for 2 quantronium. It has the advantage that the circuits are coupled by a simple fixed linear capacitor, which should not introduce further elements limiting coherence. Both qubit operate at their sweet spot and their Larmor frequencies are naturally detuned because of spread in fabrication parameters. In our proposed protocol (Fig. 10), both qubits are irradiated at their respective Larmor frequencies with a field strength giving a Rabi flop frequency equal to half their frequency separation. They are therefore placed 'on speaking terms' and will produce a gate in a period corresponding to 2 times

the inverse of the swap frequency as we have demonstrated by detailed numerical simulations. Note that our protocol is not limited to charge qubits and will work for every superconducting qubit, whether it is of the charge, flux or cavity variety.

III. Lab installation and development of new techniques

We fabricate our circuits using electron-beam lithography and multiangle e-beam vacuum deposition of metallic layers. We have installed at Yale a new nanofabrication lab for quantum circuits fabrication. This facility is also used by the groups of Rob Schoelkopf and Dan Prober. The lab consists of a field-emission scanning-electron-microscope (FEI) equipped with a pattern-generation software (Nabity), a PMMA development laminar flow bench, an e-beam evaporator (Plassys) and a Reactive Ion Etcher. We also benefit from the conventional clean room of the Yale Faculty of Engineering which houses, among other equipment, a PECVD machine for Si₃N₄ and a spin coater for our wafers.

The circuits are measured using ultra-low noise dc and microwave electrical transport techniques, at ³He refrigerator temperature (500mK-250mK) and at dilution refrigerator temperatures (10 mK – 4K). We work in a regime where the single photons of our electrical signals, whose waveform is completely controlled both in phase and amplitude, have an energy greater than the energy of thermal fluctuations.

One dilution refrigerator specially designed for microwave experiments (Cryoconcept Company) has been installed at Yale in July 2004 and has reached the base temperature of 10mK at the end of that month. The wiring of the qubit experiment has been completed during August 2004.

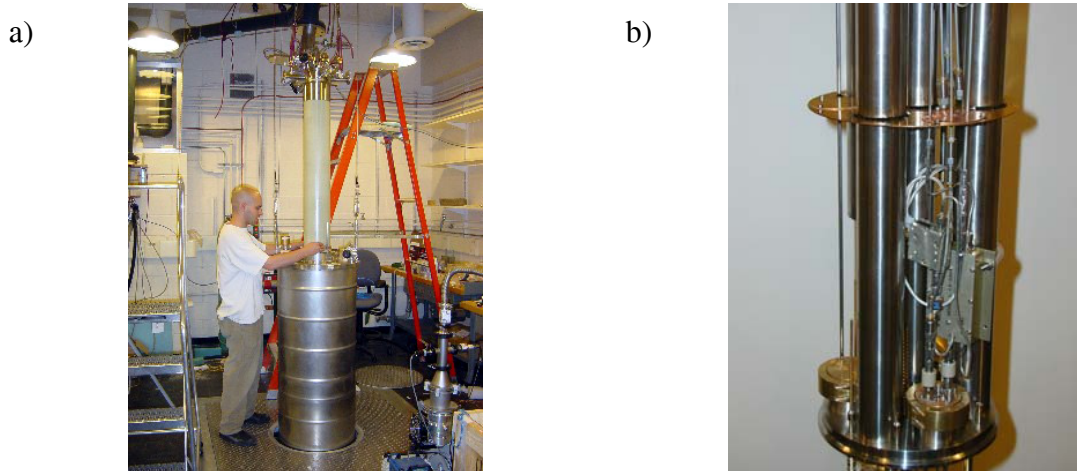


Figure 11: a) Installation at Yale in PI's lab of a new type of dilution refrigerator specially designed for RF experiments. b) Detail of microwave cabling in installation phase. Cryogenic microwave HEMT amplifier is shielded in aluminum box above 4K flange shown at the bottom of picture.

IV. Articles completed and/or published during this grant

'Manipulating the quantum state of an electrical circuit,' Vion D., Aassime A., Cottet A., Joyez P., Pothier H., Urbina C., Esteve D., and Devoret M.H., *Science*, **296**, 886-889 (2002).

'Qubits as Spectrometers of Quantum Noise,' R. J. Schoelkopf, and A.A. Clerk and S.M. Girvin and K.W. Lehnert and M.H. Devoret, in *Quantum Noise in Mesoscopic Physics*, pp. 175-203, ed. by Yu.V. Nazarov (Kluwer Ac. Publ. 2003).

'Nonequilibrium Quasiparticles and $2e$ Periodicity in Single-Cooper-Pair Transistors,' Aumentado J., Keller M. W., Martinis J. M. and Devoret M. H., *Phys. Rev. Lett.* **92**, 066802 (2004)

'An RF-Driven Josephson Bifurcation Amplifier for Quantum Measurements,' I. Siddiqi, R. Vijay, F. Pierre, C.M. Wilson, M. Metcalfe, C. Rigetti, L. Frunzio, M.H. Devoret, *Phys. Rev. Lett.* **93**, 207002 (2004) [cond-mat/0312623]

'Direct Observation of Dynamical Switching between Two Driven Oscillation States of a Josephson Junction', I. Siddiqi, R. Vijay, F. Pierre, C.M. Wilson, L. Frunzio, M. Metcalfe, C. Rigetti, R.J. Schoelkopf, M.H. Devoret, D. Vion and D. Esteve *Phys. Rev. Lett.* **94**, 027005 (2005) [cond-mat/0312553]

'Geometric Approach to Digital Quantum Information, C. Rigetti, R. Mosseri, and M. H. Devoret *J. Quantum Information Processing* **3**, 163-203 [quant-ph/0312196]

'Universal Two-Qubit Gates for Superconducting Qubits,' C. Rigetti and M. H. Devoret, *Phys. Rev. Lett.* **94**, 240502 (2005)

'Implementing Qubits with Superconducting Integrated Circuits', M.H. Devoret and J. Martinis, *Quantum Information Processing* **3**, 351-380 (2004)

'Superconducting Qubits: A Short Review', M.H.Devoret, A. Wallraff and J. M. Martinis, [cond-mat/0411174]

'The Josephson Bifurcation Amplifier for Quantum Measurements,' I. Siddiqi, R. Vijay, M. Metcalfe, E. Boaknin, L. Frunzio, R.J. Schoelkopf and M.H. Devoret preprint cond-mat/ 0507248, To be published in the proceedings of the 2004 MQC2 conference

'Dispersive measurement of superconducting qubit coherence with a fast, latching readout,' Siddiqi I., Vijay R., Metcalfe M., Frunzio L., E. Boaknin and Devoret M.H., preprint cond-mat/ 0507548. To be published in *Phys. Rev.*

'The Cavity Bifurcation Amplifier,' E. Boaknin, M. Metcalfe, V. Manucharian, L. Frunzio, R.. Schoelkopf and M.H. Devoret, in preparation